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# Net Basal Area Response 9 Years after Fertilizing Thinned and Unthinned Douglas-fir

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# Net Basal Area Response 9 Years after Fertilizing Thinned and Unthinned Douglas-fir

by

Stephen A.Y. Omule

B.C. Ministry of Forests
Research Branch
31 Bastion Square
Victoria, B.C.
V8W 3E7

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Forestry Canada
Pacific Forestry Centre
506 West Burnside Road
Victoria, B.C. V8Z 1M5
(604) 388-0600

or

B.C. Ministry of Forests
Research Branch
31 Bastion Square
Victoria, B.C. V8W 3E7
(604) 387-6719

## ABSTRACT

Equations to estimate net basal area response of Douglas-fir to nitrogen fertilization in terms of initial stand attributes were developed, based on remeasurement data over a period of 9 years from 176 plots (0.05-0.10 ha in size) of the British Columbia Forest Productivity Committee study. The data suggest that, in the slightly dry, nutrient-poor to medium sites in the CWHxm1 subzone on Vancouver Island, fertilizing immature Douglas-fir stands has several effects:

- On the average, it results in a stand net basal area cumulative response of about 5% (2.0 $m^2$/ha) in the unthinned stands, and about 7% (3.2 $m^2$/ha) in the thinned stands, after 9 years with a single application of 225 kg N/ha.
- Doubling the fertilizer dosage from 225 kg N/ha to 450 kg N/ha on the average increased stand net basal area relative response 1.5-fold to about 11% in the thinned stands, but had no effect on the unthinned-stand response, after 9 years.
- Net basal area annual response dissipates within 9 years in the unthinned stands, but persists after 9 years (probably as indirect response) in the thinned stands.

The relationship of stand response to initial stand attributes could not be detected or was confounded by the association between the initial stand attributes. Note, however, that the range of site and stand conditions in the data was relatively small. The average values of the initial stand attributes were: total age (37 years), basal area (40 $m^2$/ha), and site index (26 m at 50 years total age).



## ACKNOWLEDGEMENTS

The EP 703 study was initiated by the Ministry of Forests' Forest Productivity Committee, and subsequently maintained by Research Branch under the technical direction of P.R. Barker. Plot remeasurements and data edits, funded largely through the Canada/B.C. Intensive Forest Management Subsidiary Agreement and the Ministry of Forests' direct delivery component of the Canada/B.C. Forest Resource Development Agreement, were done by Inventory Branch. G.A. Godfrey, former Statistical Analyst for the study, compiled the stand data summaries analyzed in this report. B. Armitage and L. Darling, both research consultants, conducted the statistical analyses of the data. R.Carter (University of British Columbia) provided the revised ecological site classifications of the Douglas-fir plots. I thank G.M. Bonnor (Forestry Canada); R.O. Curtis (U.S. Department of Agriculture, Forest Service); R. Elder (Fletcher Challenge Canada Ltd.); K. Iles (MacMillan Bloedel Ltd.); K. Stagemoeller (University of Washington, College of Forest Resources); G. Weetman (University of British Columbia); and R. Brockley, K. Mitchell, and J. Thrower (Research Branch) for reviewing the draft manuscript; and the staff of the Research Branch, Communications and Extension Services section for providing editorial and publication services.

## TABLE OF CONTENTS


ABSTRACT ..... iii

ACKNOWLEDGEMENTS ..... iii

1 INTRODUCTION ..... 1

2 METHODOLOGY ..... 2

2.1 Study Design and Establishment ..... 2

2.2 The Data ..... 3

2.3 Data Analysis ..... 3

3 RESULTS AND DISCUSSION ..... 6

3.1 No Thinning ..... 6
3.1.1 Low dosage (225 kg N/ha) ..... 6
3.1.2 High dosage (450 kg N/ha) ..... 7

3.2 Light Thinning ..... 7
3.2.1 Low dosage (225 kg N/ha) ..... 9
3.2.2 High dosage (450 kg N/ha) ..... 9

3.3 Heavy Thinning ..... 9
3.3.1 Low dosage (225 kg N/ha) ..... 9
3.3.2 High dosage (450 kg N/ha) ..... 9

3.4 Comparison among Thinning Treatments ..... 9

4 SILVICULTURAL OPPORTUNITIES ..... 10

5 CONCLUSIONS ..... 12

6 REFERENCES ..... 13

## APPENDICES


1 Development of response equations ..... 14
Control yield estimates ..... 14
Response models ..... 14

2 Equations to estimate fertilizer response ..... 16
Equations to estimate response ..... 16
Equations to estimate control (untreated) yield ..... 19


## TABLES


1 Distribution of EP 703 Douglas-fir plots by site unit ..... 4

2 Mean stand net basal area response estimates by treatment, based on average values of the initial stand attributes ..... 6

3 Mean crop tree net basal area response estimates by treatment, based on average values of the initial stand attributes ..... 7

4 Shawnigan Lake study fertilizer volume response based on projections from Duke *et al.* (1989) 12


## FIGURES


1 Approximate location of the 85 installations for EP 703 ..... 2

2 Thinning and fertilizer dosage levels for EP 703 ..... 3

3 Frequency distribution of study plots by initial stand attributes ..... 4

4 Net basal area annual response by treatment over a 9-year period ..... 8

5 The relationship between stand net basal area annual response and initial age and basal area 8

6 Development of stand net basal area by treatment ..... 11

7 Development of crop-tree net basal area by treatment ..... 11

# 1 INTRODUCTION

Fertilizing Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forests with nitrogen (N) can temporarily boost tree growth and accelerate stand dynamics. The potential magnitude and duration of the response may vary with fertilizer dose and type, site characteristics such as soil moisture and nutrient status, environmental conditions, and tree and stand history. However, it is uncertain what the relationship is between these interim benefits and the stand yield and value at final harvest.

Response estimates obtained from studies of fertilizing Douglas-fir with N published in the Pacific Northwest (e.g., Barclay and Brix 1985; Miller *et al.* 1986; Miller *et al.* 1988; Stagemoeller and Chappell 1988) suggest that N improves tree growth on a variety of sites. The response estimates vary in magnitude, tending to be greater as dosage increases; larger in younger stands relative to the old; and greater in thinned stands than the unthinned (provided a sufficient number of elite trees are left).[1]

This report presents empirical regression equations for predicting response of thinned and unthinned immature Douglas-fir to N fertilization in some sites in the eastern variant of the very dry maritime Coastal Western Hemlock (CWHxm1) subzone.[2] It is based on 9 years of measurement and observation from the B.C. Ministry of Forests, Research Branch Experimental Project (EP) 703, the largest single study undertaken in British Columbia on the impact of silvicultural practices on growth and yield. Well-designed and regularly measured, the EP 703 study was to determine growth response of coastal Douglas-fir and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) to thinning and nitrogen fertilization.

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[1] For a thorough literature review of experimental fertilization of coastal Douglas-fir in the Pacific Northwest, see P. R. Barker and G.A. Godfrey. 1986. Extensive studies of fertilizing and thinning in coastal Douglas-fir and western hemlock. I. Literature review and establishment report (Draft). B.C. Min. For., Research Branch, EP 703 file report. Victoria, B.C.

[2] K. Klinka, J. Pojar, and D. Meidinger. 1989. Revision of zonal classification in coastal British Columbia. (Manuscript submitted for publication in Northwest Science ).

# 2 METHODOLOGY

## 2.1 Study Design and Establishment

The study methodology of EP 703 is described in detail in the project's establishment report (Darling and Omule 1989). The study consists of 7 industrial, 6 juvenile, and 72 standard installations located in pure and mixed Douglas-fir and western hemlock plantations and natural stands of various ages, site indices, soil types, and environmental conditions in the Vancouver Forest Region (Figure 1).

The installations were established over a 5-year period from 1971 to 1975. Industrial installations received operationally applied treatments; juvenile and standard installations received carefully controlled treatments, as described later in this section. Unlike the standard installations, the juvenile installations were specifically located in stands less than 15 years old, and do not have pre-treatment measurements. This report is based on 17 standard installations located in pure (greater than 80% by volume) Douglas-fir stands in the CWHxm1 subzone.

Design of the standard installations was a randomized complete block, with a partial two-factor factorial arrangement. The factors were thinning and fertilizer dosage, with 4 and 5 levels, respectively (Figure 2). Each treatment combination was replicated twice. Each replicate is a square 0.05-, 0.07-, or 0.10-ha plot. Blocking was based on pre-treatment plot basal area. The number of plots per installation ranged from 4 to 32, with a typical installation consisting of 18 plots. Some installations have no control plots and some consist of only one of two factors.

Nitrogen in the form of prilled urea (46% N) was applied by hand over the plot and buffer, in the fall or early spring prior to thinning. The dosages ranged from 0 to 900 kg N/ha. The thinning was a crown thinning, removing 0-50% of the plot initial basal area.

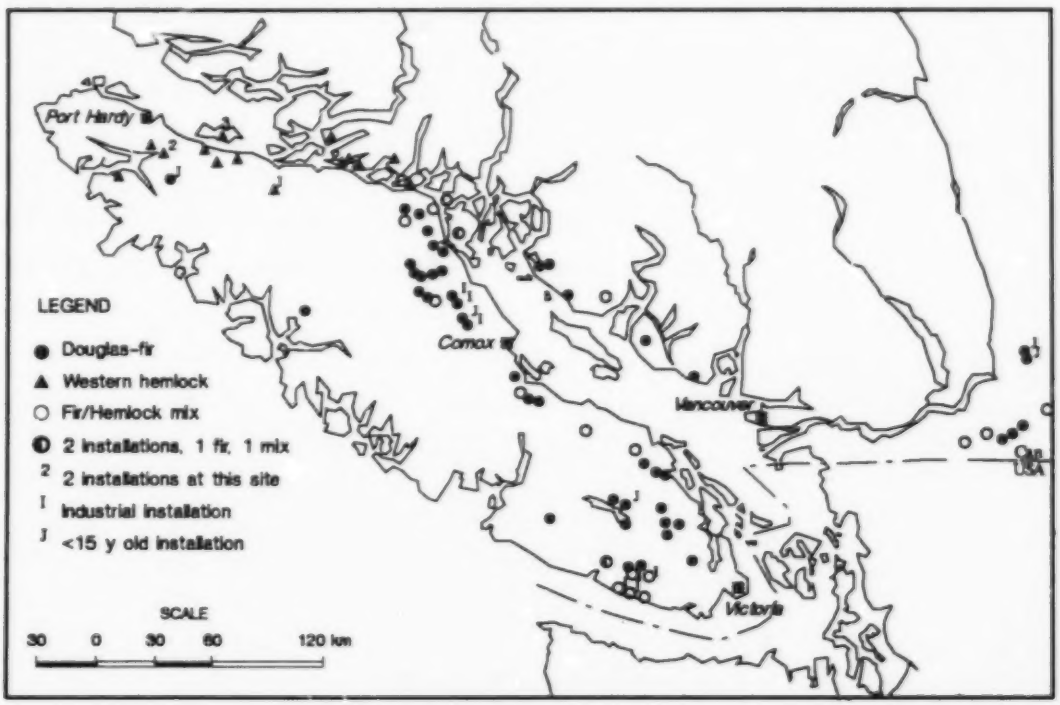


FIGURE 1. Approximate location of the 85 installations for EP 703.

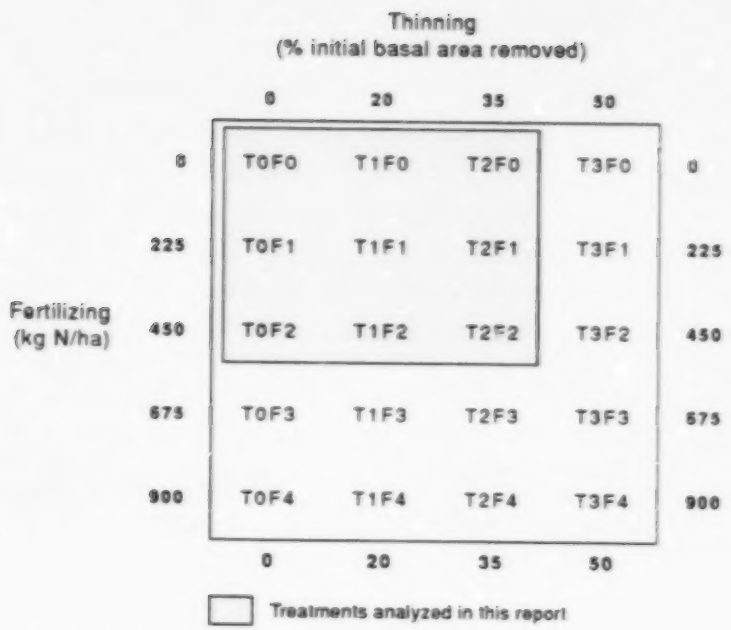


FIGURE 2. Thinning and fertilizer dosage levels for EP703. In the figure, T stands for thinning, F stands for fertilization, and the numbers following each letter are treatment level serial numbers.

## 2.2 The Data

Measurements of the dbh of all trees and of the total height of a sample of trees in each plot were made before and immediately after treatment and four times at 3-year intervals thereafter. Ingrowth (dbh threshold: 5.0 cm) was measured, but not cut.

Entire-stand and crop-tree net basal areas (basal area per hectare of live standing trees, excluding ingrowth) were obtained from individual tree measurements of dbh for each plot and period of measurement up to 9 years after treatment. Summaries of the tree measurements 12 years after treatment were not available. Summaries of crop trees (the most valuable trees expected at final harvest) were obtained by tracing back the growth of 13, 18, and 25 live trees per 0.05-, 0.07-, and 0.10-ha plot, respectively (250 trees per hectare), that were the largest by dbh 9 years after treatment.

Site index was estimated at plot establishment according to Hegyi *et al.*'s (1981) site curves. Total age was estimated from increment cores of a subsample of trees in each plot. Plot frequency distribution by initial site index, total age, and basal area is depicted in Figure 3.

## 2.3 Data Analysis

Regression analyses based on the net basal area summaries were used to quantify fertilizer response in terms of stand attributes at time of fertilization.[3] The data analysis was limited to the CWHxm1 slightly dry, nutrient-poor to medium site (Site Unit 2)[4], in which a reasonable number of study plots was located (Table 1).

---

[3] Fertilizer response was based on stand basal area rather than volume to avoid errors due to inadequate and inconsistent sampling for tree heights (Darling and Omule 1989, p.10). However, as pointed out by R.O. Curtis (USDA, Portland, Oreg., pers. comm., July 1989), it may be risky to substitute basal area for volume because, in general, basal area response and volume response are not equivalent and may behave quite differently in certain instances.

[4] A site unit represents a group of closely related forest sites which can support forest stands of the same composition and structure, have similar production potential, and can be managed by the same silvicultural system (Klinka *et al.* 1984, p. 110).

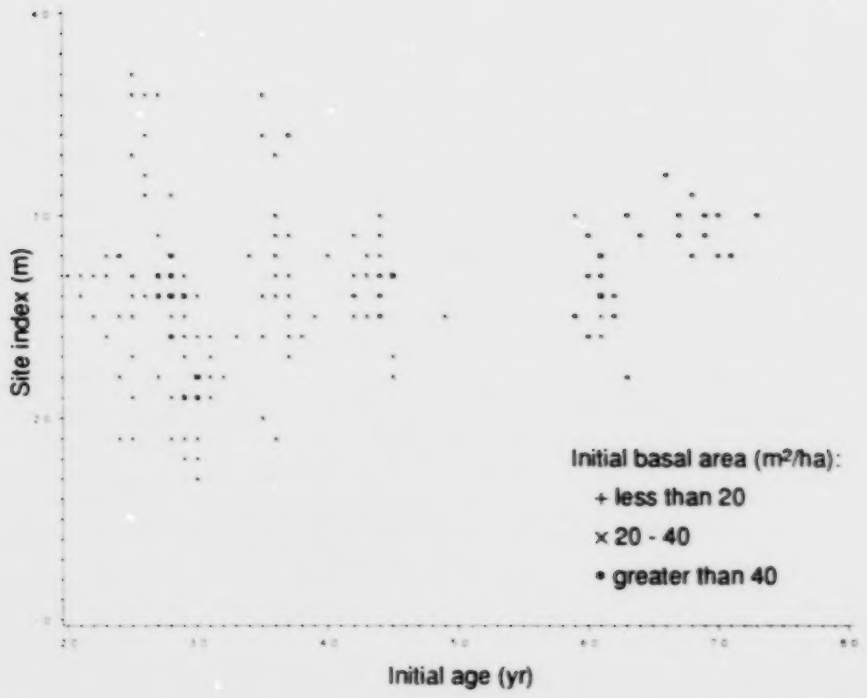


FIGURE 3. Frequency distribution of study plots by initial stand attributes.

TABLE 1. Distribution of EP 703 Douglas-fir plots by site unit

| Site unit[a] | Total number installations | Total number plots | Average number plots/installations[b] |
|---|---|---|---|
| 1 | 5 | 44 | 10(5) |
| 2[c] | 17 | 204 | 12(5) |
| 3 | 6 | 64 | 11(4) |
| **Total** | **28** | **312** | |

[a] Site units within the CWHxm1 subzone. A site unit represents a group of closely related forest sites which can support forest stands of the same composition and structure, have similar production potential, and can be managed by the same silvicultural system (Klinka *et al.* 1984, p. 110). The classifications were conducted by R.E. Carter of the Univ. of B.C., Faculty of Forestry, Vancouver, B.C.

[b] Values in brackets are standard deviations.

[c] Only the data in this site unit were used in the report. Two installations were discarded as outliers.

As well, only three levels each of thinning (0, 20, and 35% initial basal area removed) and fertilizer dosage (0, 225, and 450 kg N/ha) were considered. A regression approach was used because the study design was unbalanced (Darling and Omule 1989, p. 3) and measurements were not taken at the same points in time in all the plots.

The analysis focused on answering the following questions for both the thinned and unthinned Douglas-fir stands:

- Is there a fertilizer net basal area response, and how long does it last?
- What effect does fertilizer dosage have on the response?
- What effect does thinning have on the response?
- How does the response vary with stand age, density, and site index?

Equations to predict stand and crop tree response were developed based on two-stage regression analysis (West *et al.* 1984). The following three-step procedure was used.

1. Equations were fitted to estimate net basal area in the unfertilized (control) plots for each control treatment combination (T0F0, T1F0, and T2F0), as functions of time since treatment and stand attributes (age, basal area, and site index) at time of fertilization.[5]
2. Cumulative response to fertilization was calculated in each fertilized plot as the difference between the observed net basal area of the fertilized plot and its predicted net basal area as an unfertilized plot having the same initial stand attributes. That is, equations in step 1 were used to predict how the net basal area would have developed in the fertilized plots had they not been fertilized. The T0F0 equation was used in the T0F1 and T0F2 plots; the T1F0 equation was used in the T1F1 and T1F2 plots; and the T2F0 equation was used for the T2F1 and T2F2 plots.
3. Equations were fitted to the calculated cumulative responses in step 2, to estimate response in the fertilized plots for each treatment combination (T0F1, T0F2, T1F1, T1F2, T2F1, and T2F2) as functions of initial stand attributes and time since treatment.

Response surfaces generated from the response equations in step 3 were examined graphically to provide answers to the questions posed above.

Response estimates obtained in this fashion (sometimes called smoothed estimates) are precise, but are very sensitive to data and models used.[6] Two-stage regression analysis was used to reduce the possible effects of the serial correlation inherent in the repeated measurements in the plots. Further details of the analyses are given in Appendix 1.

---

[5] Stand structure at time of treatment was not included because preliminary analyses to describe the left-truncated plot diameter distributions using the Weibull function were unsuccessful for about one-half of the plots; and, for those distributions that were successfully fitted, the Weibull parameters were inconsistent among plots pooled by installation and treatment, including the control.

[6] James A. Moore, Univ. of Idaho, Moscow, Idaho, pers. comm., April 1989.

# 3 RESULTS AND DISCUSSION

Equations for estimating net basal area response of coastal Douglas-fir to specific fertilization and thinning treatments are presented in Appendix 2. They require knowledge of initial stand age, basal area, and site index. Questions posed in the Data Analysis section are answered in the Conclusions section. Comparisons of the 9-year net basal area response among fertilizer levels and among thinning treatments are briefly discussed below. Tables 2 and 3 contain summaries of the estimated responses corresponding to the average initial stand values represented by the study data. The values and relationships in Table 2 may differ from those reported by Miller *et al.* (1986, Figure 3). Their data included additional Douglas-fir standard installations which covered a wider range of site and ecological conditions.

TABLE 2. Mean stand net basal area response estimates by treatment, based on average values of the initial stand attributes

| Treat. code[c] | No. plots | Time since treat. (yr) | Cumulative response[a] | | | Annual response[b] | |
|---|---|---|---|---|---|---|---|
| | | | Absolute "actual"[e] ($m^2$/ha) | Absolute predicted[f] ($m^2$/ha) | Relative[d] (%) | Absolute ($m^2$/ha/yr) | Relative (%) |
| T0F1 | 18 | 3 | 1.2(0.24)[g] | 1.3 | 3 | 0.23 | 19 |
| | | 6 | 2.2(0.37) | 1.8 | 5 | 0.11 | 10 |
| | | 9 | 2.3(0.52) | 2.0 | 5 | 0.06 | 5 |
| T0F2 | 18 | 3 | 1.7(0.22) | 2.0 | 4 | 0.35 | 30 |
| | | 6 | 2.5(0.53) | 2.7 | 6 | 0.17 | 15 |
| | | 9 | 2.6(0.58) | 3.1 | 6 | 0.08 | 8 |
| T1F1 | 18 | 3 | 1.4(0.34) | 1.7 | 4 | 0.34 | 32 |
| | | 6 | 2.6(0.50) | 2.5 | 7 | 0.25 | 23 |
| | | 9 | 2.9(0.71) | 3.2 | 7 | 0.21 | 18 |
| T1F2 | 18 | 3 | 2.1(0.31) | 2.0 | 6 | 0.54 | 50 |
| | | 6 | 3.5(0.48) | 3.4 | 10 | 0.39 | 36 |
| | | 9 | 4.3(0.61) | 4.5 | 11 | 0.33 | 29 |
| T2F1 | 18 | 3 | 1.3(0.25) | 0.7 | 5 | 0.25 | 22 |
| | | 6 | 2.3(0.45) | 1.3 | 7 | 0.19 | 16 |
| | | 9 | 2.6(0.64) | 1.9 | 7 | 0.20 | 15 |
| T2F2 | 18 | 3 | 1.8(0.36) | 2.3 | 7 | 0.67 | 59 |
| | | 6 | 3.4(0.81) | 4.2 | 11 | 0.58 | 48 |
| | | 9 | 3.9(1.22) | 5.8 | 11 | 0.52 | 39 |

[a] Average difference in basal area between fertilized and control plots.
[b] Average amount by which basal area annual growth of fertilized plots exceeds that of the control: predicted from the response equations (Appendix 2).
[c] See Figure 2 for definition of treatment codes.
[d] Based on the predicted smoothed estimates.
[e] Smoothed responses before fitting the response equations.
[f] Responses predicted from the response equations (Appendix 2) for comparison with the "actual".
[g] Values in brackets are standard errors.

## 3.1 No Thinning

### 3.1.1 Low dosage (225 kg N/ha)

Stand cumulative response was about 5% (2.0 $m^2$/ha) 9 years after fertilization. Crop trees, which constituted about 37% of the initial stand basal area, accounted for about 60% of the stand response. Most of the stand response appears to have dissipated at 9 years, as indicated by a sharp decline in absolute annual response (Figure 4). The rapid decline in stand net response was probably due to non-crop tree mortality.

The relationship of stand and crop-tree response to initial stand attributes was not detectable. Note, however, that the range of site and stand conditions in the data was relatively small.

TABLE 3. Mean crop tree net basal area response estimates by treatment, based on average values of the initial stand attributes

| Treat. code[c] | No. plots | Time since treat. (yr) | Cumulative response[a] | | | Annual response[b] | |
|---|---|---|---|---|---|---|---|
| | | | Absolute "actual"[e] ($m^2$/ha) | Absolute predicted[f] ($m^2$/ha) | Relative[d] (%) | Absolute ($m^2$/ha/yr) | Relative (%) |
| T0F1 | 18 | 3 | 0.4(0.08) | 0.7 | 3 | 0.11 | 22 |
| | | 6 | 0.8(0.13) | 1.0 | 5 | 0.08 | 17 |
| | | 9 | 0.9(0.16) | 1.2 | 6 | 0.08 | 14 |
| T0F2 | 18 | 3 | 0.7(0.05) | 0.9 | 5 | 0.18 | 36 |
| | | 6 | 1.5(0.14) | 1.5 | 10 | 0.15 | 29 |
| | | 9 | 1.9(0.19) | 2.1 | 11 | 0.13 | 24 |
| T1F1 | 18 | 3 | 0.2(0.18) | 0.2 | 1 | 0.04 | 5 |
| | | 6 | 0.6(0.34) | 0.2 | 3 | -0.01 | -1 |
| | | 9 | 0.6(0.47) | 0.2 | 3 | -0.01 | -2 |
| T1F2 | 18 | 3 | 0.8(0.17) | 0.9 | 5 | 0.30 | 45 |
| | | 6 | 1.6(0.34) | 2.1 | 9 | 0.48 | 68 |
| | | 9 | 1.9(0.54) | 3.8 | 9 | 0.70 | 92 |
| T2F1 | 16 | 3 | 0.5(0.16) | 0.5 | 3 | 0.16 | 24 |
| | | 6 | 1.1(0.23) | 0.9 | 6 | 0.12 | 18 |
| | | 9 | 1.3(0.33) | 1.3 | 6 | 0.12 | 15 |
| T2F2 | 16 | 3 | 0.9(0.17) | 1.0 | 6 | 0.32 | 54 |
| | | 6 | 2.1(0.28) | 1.9 | 12 | 0.32 | 51 |
| | | 9 | 2.8(0.36) | 2.9 | 15 | 0.34 | 50 |

[a] Average difference in basal area between fertilized and control plots.
[b] Average amount by which basal area annual growth of fertilized plots exceeds that of the control: predicted from the response equations (Appendix 2).
[c] See Figure 2 for definition of treatment codes.
[d] Based on the predicted smoothed estimates.
[e] Smoothed responses before fitting the response equations.
[f] Responses predicted from the response equations (Appendix 2) for comparison with the "actual".

### 3.1.2 High dosage (450 kg N/ha)

Stand cumulative response was about 6% (3.1 $m^2$/ha) 9 years after fertilization. Crop trees accounted for about 67% of the stand response, despite the low proportion of crop trees (38% of the initial basal area). Most of the stand response appears to have dissipated at 9 years, as indicated by a rapid decline in annual response (Figure 4). Presumably, loss of smaller-than-average trees to competition-induced mortality may explain the rapid decline in stand net response, the large response of crop trees relative to the entire stand, and the gradual decline in crop tree response.

Stand response was greater in young stands with low basal area than in the older stands with high basal area (Figure 5). This may be partially a result of trees in the young stands, which have been subject to less competition than those in the older stands, probably having more efficient crowns to use the added nutrients. The relationships of stand response to site index and of crop tree response to initial stand attributes were not detectable or were confounded by the association between the initial stand attributes.

## 3.2 Light Thinning

Only the stand response comparisons are discussed here. The crop tree analyses were inconclusive. The developed equations underestimated and overestimated response in the low and high dosages, respectively, resulting in questionable response surfaces.

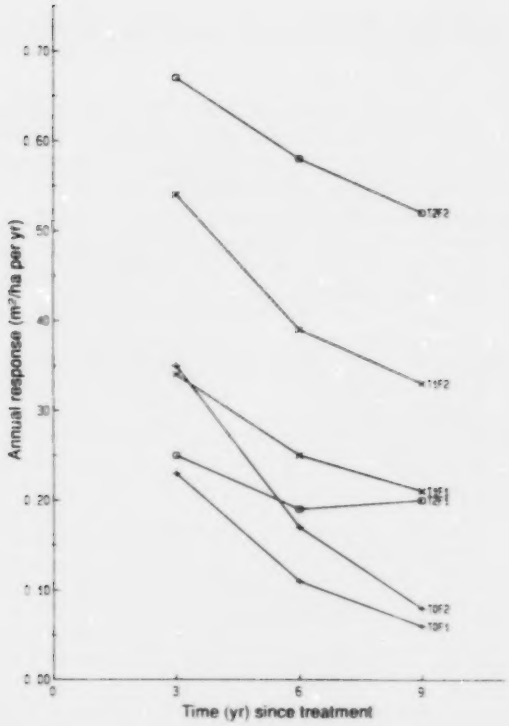


FIGURE 4. Net basal area annual response by treatment over a 9-year period.

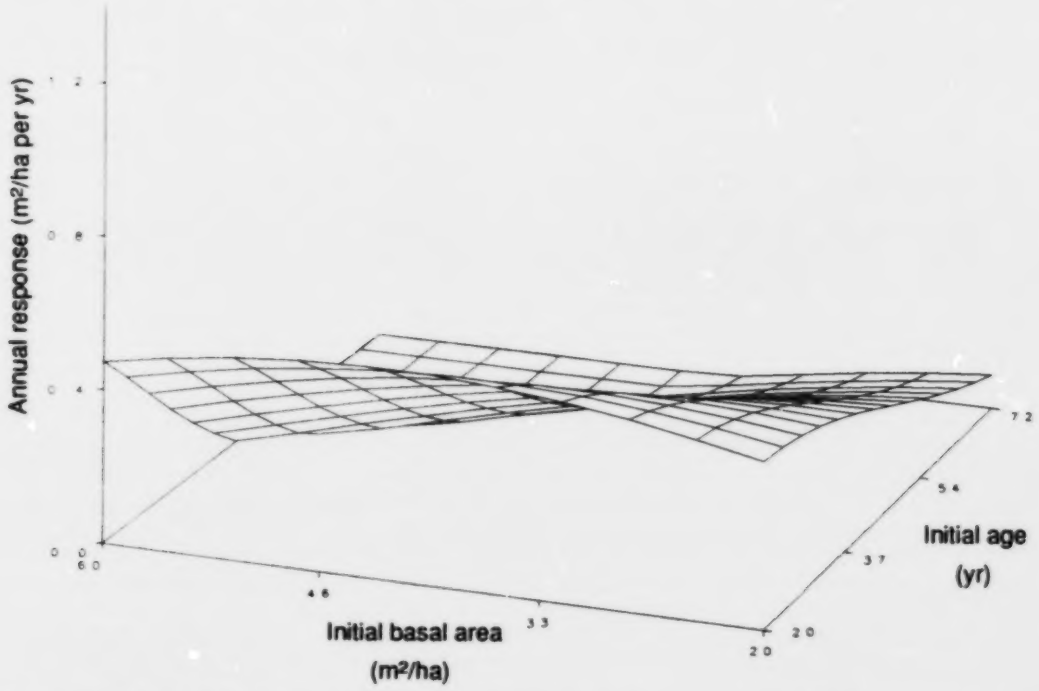


FIGURE 5. The relationship between stand net basal area annual response and initial age and basal area. The predicted annual response was at 3 years after treatment (T0F2).

### 3.2.1 Low dosage (225 kg N/ha)

Stand cumulative response was about 7% (3.2 $m^2$/ha) 9 years after fertilization. Stand annual response is declining gradually, and appears to be still significant after 9 years (Figure 4). This is presumably because of reduced mortality through thinning, and indirect fertilizer response. (Indirect fertilizer response is response due to increased diameter growth on fewer, larger trees in the fertilized stands. Direct fertilizer response is response due to improved nutrition.)

The relationship of stand response to initial stand attributes was confounded by the association between the initial stand attributes. Note, however, that the range of post-thinning initial basal area in the light thinning was relatively small.

### 3.2.2 High dosage (450 kg N/ha)

Stand cumulative response was about 11% (4.5 $m^2$/ha) 9 years after treatment. Stand annual response is declining gradually and still persisting after 9 years (Figure 4). This is presumably because of reduced mortality through thinning, and of indirect fertilizer response.

The relationship of stand response to initial stand attributes was confounded by the association between the initial stand attributes.

## 3.3 Heavy Thinning

### 3.3.1 Low dosage (225 kg N/ha)

Stand cumulative response was about 7% (3.2 $m^2$/ha) 9 years after fertilization. Crop trees, which constituted about 61% of the remaining basal area after thinning, accounted for about 68% of the stand response. Stand annual response is declining gradually and appears to be persisting after 9 years (Figure 4). This is presumably because of the indirect fertilizer response.

The relationship of stand and crop-tree responses to initial stand attributes was confounded by the association between the initial stand attributes. Note, however, that the range of post-thinning initial basal area in the heavy thinning plots was relatively small.

### 3.3.2 High dosage (450 kg N/ha)

Stand cumulative response was about 11% (5.8 $m^2$/ha) 9 years after fertilization. Crop trees, which constituted about 61% of the remaining basal area after thinning, accounted for about 50% of the stand response. Stand annual response is declining gradually and appears to be still persisting after 9 years (Figure 4), presumably because of the indirect fertilizer response.

The relationship of stand and crop-tree response to initial stand attributes was confounded by the association between the initial stand attributes.

## 3.4 Comparison among Thinning Treatments

Relative stand and crop-tree net basal area responses were generally lower in the unthinned stands than in the thinned, with the application of 225 kg N/ha or 450 kg N/ha. Doubling the fertilizer dosage had no detectable effect on the net basal area response in the unthinned stands, but it increased stand response of the thinned stands 1.5 times. This occurred because the unthinned stands initially were probably not too far from the upper density limit. Thus, any acceleration of growth produced by fertilization would be expected to increase both diameter increment and mortality rates with relatively little change in net basal area.[7]

Doubling the fertilizer dosage increased crop-tree response in the unthinned stands 1.8 times and more than doubled that in the thinned stands.

[7] R.O. Curtis, USDA, Portland, Oreg., pers. comm., July 1989.

# 4 SILVICULTURAL OPPORTUNITIES

These study results have important practical implications for the management of Douglas-fir stands in coastal British Columbia, although the thinning regimes were not designed to represent stocking levels managed today.

Equations presented in Appendix 2 can be used to estimate response of specific stands to fertilization and to evaluate potential stands for treatment in the CWHxm1 subzone. The response estimates can also be used to calibrate growth models to facilitate comparison of silvicultural treatments involving fertilization.

The following observations were made from the study.[8] They may be helpful to the forest manager who must decide whether to fertilize a given stand or not, and may be indicative of the yields to be expected from fertilized stands.

1. Fertilizing thinned stands will not restore stand net basal area to match the net basal area of the unthinned stands over a 9-year period (Figure 6).
2. Thinning by removal of 35% of initial basal area (corresponding to removal of about 800-1000 stems per hectare out of about 2000 stems per hectare) was not too severe and did not draw basal area too far to lose much basal area increment.
3. Combining fertilization with thinning results in greater gains in crop-tree net basal area response, than does fertilizing alone. For example, fertilizing thinned stands (35% initial basal area removed) will result in a 15% crop-tree cumulative response compared to a 10% cumulative response in the unthinned stands (Figure 7). In addition, combining fertilization with thinning accumulates the extra growth produced by fertilization on fewer stems, which will probably produce more valuable wood.
4. Fertilization does not drastically increase merchantable yield in thinned and unthinned stands, assuming that this study's 9-year relative net basal area yield is indicative of relative volume yield. An analysis of Duke *et al.*'s (1989) volume projections of the Shawnigan Lake study indicated that volume gains at rotation age ranged from 4 to 10% (Table 4).

The decision to fertilize or not, however, depends on consideration of several other factors, such as the economics of the fertilization, the need to overcome irregularities and shortages in wood supply, and site nutrient deficiencies.

TABLE 4. Shawnigan Lake study fertilizer volume response based on projections from Duke *et al.* (1989)

| Treat.[a] | Rotation age[c] (yr) | Volume[b] ($m^3$/ha) | Volume response | |
|---|---|---|---|---|
| | | | Absolute ($m^3$/ha) | Relative (%) |
| T2F0 | 90 | 530.6 | 0.0 | 0 |
| T2F1 | 84 | 553.0 | 22.4 | 4 |
| T2F2 | 78 | 564.0 | 23.4 | 6 |
| T1F0 | 102 | 641.0 | 0.0 | 0 |
| T1F1 | 96 | 692.0 | 51.0 | 8 |
| T1F2 | 96 | 688.0 | 47.0 | 7 |
| T0F0 | 114 | 604.0 | 0.0 | 0 |
| T0F1 | 108 | 678.1 | 37.1 | 6 |
| T0F2 | 108 | 668.0 | 27.0 | 4 |

[a] For description of treatment codes, see Duke *et al.* (1989).
[b] Merchantable volume: minimum dbh 17.5 cm.
[c] From Duke *et al.* (1989, Table 4).

[8] Some of these observations were pointed out by G. Weetman (University of British Columbia, Vancouver, B.C., pers. comm., July 1989).

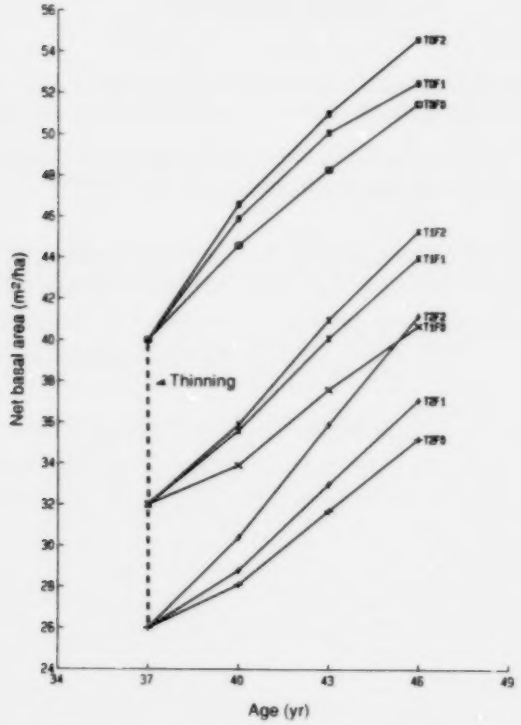


FIGURE 6. Development of stand net basal area by treatment.

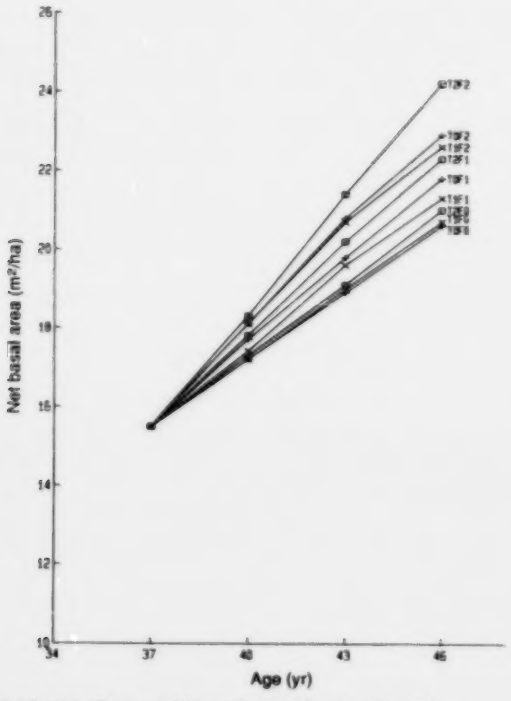


FIGURE 7. Development of crop-tree net basal area by treatment.

# 5 CONCLUSIONS

The following conclusions, in form of answers to the questions posed in the Data Analysis section, are based on net basal area. They are applicable within the range of site and stand conditions of the study.

- Douglas-fir stands can respond to N fertilization. The response appears to dissipate within 9 years in the unthinned stands. However, the response persists (probably as indirect response) after 9 years in the thinned stands.
- The stand net basal area cumulative response was about 5% (2.0 $m^2$/ha) in the unthinned stands, and about 7% (3.2 $m^2$/ha) in the thinned stands, with a single application of 225 kg N/ha.
- Doubling fertilizer dosage from 225 kg N/ha to 450 kg N/ha increases stand relative cumulative response about 1.5 times to about 11% in the thinned stands after 9 years. However, the relative cumulative response remained the same (about 5%) in the unthinned stands over the same period.
- Relative response is generally higher in the thinned stands than in the unthinned stands.
- The relationships of stand response to initial stand attributes (total age, basal area, and site index) were generally not detectable or were confounded by the association between the initial stand attributes. Note that the range of site and stand conditions in the data was relatively small.

The results from this study confirm that fertilizing Douglas-fir with N can temporarily boost stand yield on some sites. However, it is still uncertain what impact these interim benefits have on the yield at rotation age and beyond. Thus, it is important that this study be maintained past harvest age to help verify and expand these interim conclusions.

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## APPENDIX 1. Development of response equations

### Control yield estimates

In this section, control yield equations — equations to predict how the net basal area in each fertilized plot would have developed had it not been treated — were developed. Based on net basal area measurements 0, 3, 6, and 9 years after treatment, estimates of coefficients for the following model were obtained for each plot by ordinary linear least squares:

$$ln(y) = b_0 + b_1 X + b_2 ln(X + 1) \quad (1)$$

where

$X$ = time since fertilization (0, 3, 6, and 9 years)
$y$ = net basal area at time $X$ ($m^2$/ha)
$b_i$ = regression coefficients ($i$ = 0,1,2).

Model (1) was chosen after examination of graphs of $y$ over $X$ for several plots. According to Curtis and Marshall (1986, p. 41), the above model is fairly flexible and can represent a relationship with a maximum while also giving a reasonable approximation to asymptotic relationships.

For each set of control plots — T0F0, T1F0, or T2F0 — the regression coefficients $b_i$ were analysed as new characteristics. Each $b_i$ corresponding to each data set was related to initial stand attributes $Z_i$ (specifically, initial stand basal area, total age, and site index, or their suitable transformations):

$$\hat{b}_i = f_i(Z_1; Z_2; Z_3; \ldots) \quad (2)$$

for $i$ = 0,1,2. Graphical methods and the $C_p$ criterion (e.g., SAS Institute Inc. 1985, p. 765) were used to select the best independent variables $\{Z_i\}$ to enter equations (2) and to check the fit of the models. The selected second-stage equations in (2) were substituted back into equation (1), to give the control yield equation:

$$ln(\hat{y}) = f_0 + f_1 X + f_2 ln(X + 1) \quad (3)$$

which was then used to predict how each treated plot would have developed had it not been fertilized.

Residuals of the complete model, after selection of the second-stage regressions, were plotted against initial stand attributes to detect any existing relationships.

The control yield equation (3) was differentiated with respect to $X$ (time since fertilization) to give the control annual growth model for each set of control plots:

$$m = d\hat{y}/dX = e^{b_0}\{e^{b_1 X} b_2 X^{b_2 - 1} + X^{b_2} b_1 e^{b_1 X}\} \quad (4)$$

### Response models

In this section, equations to predict cumulative response to fertilization in each plot were developed based on two-stage regression analysis. Cumulative response to fertilization in a plot was calculated as the difference between the observed values of net basal area of the treated plot and the smoothed "control" profile (equation (3) above).

Using the estimated cumulative responses at each of 3, 6, and 9 years, the coefficients for the following model were estimated for each plot by ordinary linear least squares:

$$r = e^{c_0 + c_1 X} X^{c_2} \quad (5)$$

or, in the form fitted

$$ln(r + k) = c_0 + c_1 X + c_2 ln(X + 1)$$

where

$r$ = estimated cumulative response at time $X$ (m²/ha)
$X$ = time since fertilization (0, 3, 6, 9 years)
$c_i$ ($i$ = 0,1,2) = regression coefficients
$k$ = an arbitrary constant large enough to offset negative responses.

For each set of treated plots — T0F1, T0F2, T1F1,T1F2, T2F1,or T2F2 — the regression coefficients $c_i$ were analysed as new characteristics. Each $c_i$ corresponding to each data set was related to initial stand attributes $\{Z_i\}$ or their suitable transformations:

$$c_i = g_i(Z_1; Z_2; Z_3; \ldots) \tag{6}$$

for i = 0,1,2. Graphical methods and the $C_p$ criterion were used to select the best independent variables to enter into equations (6) and to check the fit of the models. The selected second-stage equations in (6) were substituted back into equation (5) to give the response equation

$$\hat{r} = e^{g_0 + g_1 X} X^{g_2} \tag{7}$$

Residuals of the complete model, after selection of the second-stage regressions, were plotted against initial stand attributes to detect any existing relationships.

The cumulative response equations were differentiated with respect to X (time since fertilization), to give annual response model:

$$s = d\hat{r}/dX = e^{c_0}\{e^{c_1 X} c_2 X^{c_2 - 1} + X^{c_2} c_1 e^{c_1 X}\} \tag{8}$$

Relative response was obtained as

$$\hat{r}\% = 100\hat{r}/\hat{y} \tag{9}$$

Relative annual response was obtained as

$$s\% = 100s/m \tag{10}$$

The theoretical time $X^0$ it takes for the fertilizer treatment annual response to dissipate completely was obtained by setting $s$ = 0 in equation (7) and then solving for $X$ to give:

$$X^0 = -c_2/c_1 \tag{11}$$

Note that the significant portion of the fertilizer annual response will probably have dissipated well before time $X^0$.

## APPENDIX 2. Equations to estimate fertilizer response

### Equations to estimate response

The response equations are of the general form

Cumulative response: $r = e^{(c_0 + c_1 X)} X^{b_2} - k$

Annual response: $\frac{dr}{dX} = e^{c_0}(e^{c_1 X} c_2 X^{c_2 - 1} + X^{c_2} c_1 e^{c_1 X})$

Details of the fitting procedure are given in Appendix 1. The following tables (A2.1 and A2.2) give the values or equations for estimating the $c_i$ coefficients.

The following variables are used in the equations:

| | | |
|---|---|---|
| SITEAGE | = | SITE * IAGE; |
| AGEBA | = | IAGE * IBA; |
| SITEBR | = | SITE * BR; |
| IAGERR | = | IAGE * BR; |
| SITEBA | = | SITE * IBA; |
| IBABR | = | IBA * BR; |
| IAGE | = | Initial age in years; |
| IBA | = | Initial basal area in $m^2$/ha; for the thinned plots IBA is remaining basal area after thinning; |
| IBAC | = | Initial basal area of crop trees in $m^2$/ha; |
| SITE | = | Initial site index: metres at 50 years total age, based on Hegyi *et al.*'s (1981) site curves; |
| BR | = | Proportion of initial basal area cut. |

TABLE A2.1. Coefficients for estimating stand response

| Treat. | Coefficient ($c_i$) | Value or equation of coefficient | Adj. $R^2$ | $\sqrt{MSE}$ |
|---|---|---|---|---|
| T0F1 | $c_0$ | 1.629100 | | |
| | $c_1$ | −0.0095200 | | |
| | $c_2$ | 0.1812500 | | |
| | $k$ | 5 | | |
| T0F2 | $c_0$ | $0.008699 + (0.028730\ IAGE)$ $-(0.000463\ IAGE^2)$ $+(0.050261\ IBA)$ $-(0.000410\ IBA^2)$ | 0.4567 | 0.092 |
| | $c_1$ | −0.017330 | | |
| | $c_2$ | $0.435312 - 0.000138\ AGEBA$ | 0.4604 | 0.195 |
| | $k$ | 5 | | |
| T1F1 | $c_0$ | $2.283720 - 0.043392\ IBA$ $+0.000660\ IBA^2$ | 0.2906 | 0.077 |
| | $c_1$ | $-0.06592 + 0.002464\ IBA$ | 0.2484 | 0.034 |
| | $c_2$ | $0.721025 - 0.027756\ IBA$ $+0.000242\ AGEBA$ | 0.4296 | 0.101 |
| | $k$ | 2.5 | | |
| T1F2 | $c_0$ | $1.245639 - 0.043614\ SITE$ | 0.4271 | 0.191 |
| | $c_1$ | $-0.057903 + 0.009842\ IBA$ $-1.408778\ BR$ | 0.5581 | 0.071 |
| | $c_2$ | $5.103099 - 0.243314\ IBA$ $+0.003125\ IBA^2$ | 0.4564 | 0.348 |
| | $k$ | 5 | | |
| T2F1 | $c_0$ | $-1.621779 + 0.181485\ SITE$ $-0.003382\ SITE^2$ | 0.4567 | 0.109 |
| | $c_1$ | $-7.560738 + 40.967606\ BR$ $-54.992373\ BR^2$ | 0.4984 | 0.084 |
| | $c_2$ | $e^{0.616377-0.59181\ SITE}$ | 0.1749 | 0.560 |
| | $k$ | 1 | | |
| T2F2 | $c_0$ | $-0.751648 + 2.378744\ BR$ | 0.3172 | 0.116 |
| | $c_1$ | $-0.361265 + 0.000612\ SITEAGE$ $-0.000000229\ SITEAGE^2$ | 0.5527 | 0.040 |
| | $c_2$ | $1.969577 - 0.002232\ SITEAGE$ $+0.001035\ AGEBA$ | 0.4418 | 0.262 |
| | $k$ | 1 | | |

TABLE A2.2. Coefficients for estimating crop tree response

| Treat. | Coefficient ($c_i$) | Value or equation of coefficient | Adj. $R^2$ | $\sqrt{MSE}$ |
|---|---|---|---|---|
| T0F1 | $c_0$ | $1.737594 + 0.009463\,IAGE$ $-0.00009475\,IAGE^2 + 0.00006394\,SITE^2$ | 0.4104 | 0.028 |
| | $c_1$ | 0.00617 | | |
| | $c_2$ | 0.03048 | | |
| | $k$ | 7 | | |
| T0F2 | $c_0$ | $1.707010 + 0.008900\,IAGE$ $-0.000093169\,IAGE^2 + 0.000122\,SITE^2$ | 0.4622 | 0.027 |
| | $c_1$ | $e^{-2.829369-0.000270\,SITEBA} - 0.03$ | 0.1899 | 0.246 |
| | $c_2$ | $[736.801968 + 12.611472\,SITE$ $-322.986137\,ln(SITE)]^{-1} - 0.04$ | 0.2658 | 4.599 |
| | $k$ | 5 | | |
| T1F1 | $c_0$ | $e^{0.405593-0.006164\,IBA+0.00867\,SITE}$ | 0.7386 | 0.027 |
| | $c_1$ | $0.453474 - 0.010454\,SITE - 0.02$ | 0.3240 | 0.059 |
| | $c_2$ | $e^{1698.726647-(7149.60145/SITE)}$ $\cdot\, e^{-510.03108\,ln(SITE)+9.070477\,SITE}$ | 0.7866 | 0.641 |
| | $k$ | 4 | | |
| T1F2 | $c_0$ | $e^{11.037872+0.664165\,SITEBR-16.718213\,BR}$ $\cdot\, e^{-3.281972\,ln(SITE)}$ | 0.6152 | 0.070 |
| | $c_1$ | $-11.233392 + 0.164828\,IBA$ $+0.437966\,SITE + 36.337835\,BR$ $-0.006235\,SITEBA - 1.432104\,SITEBR$ | 0.6020 | 0.173 |
| | $c_2$ | $e^{15.977235-7.218847\,ln(IBA)+0.007523\,SITEBA}$ | 0.7512 | 0.472 |
| | $k$ | 7 | | |
| T2F1 | $c_0$ | $e^{-3.37176+1.120011\,ln(IAGE)}$ $\cdot\, e^{-0.001219\,SITEAGE+0.031962\,SITE}$ | 0.4353 | 0.089 |
| | $c_1$ | $e^{-7.637027-0.009101\,SITEAGE}$ $\cdot\, e^{0.438665\,SITE+0.666407\,IAGEBR}$ $\cdot\, e^{-0.41601\,SITEBR} - 0.1$ | 0.7248 | 0.295 |
| | $c_2$ | $e^{-34.850569+1.454711\,IBA+101.249912\,BR}$ $\cdot\, e^{-4.049662\,IBABR-0.41601\,SITEBR}$ | 0.6138 | 0.516 |
| | $k$ | 5 | | |
| T2F2 | $c_0$ | $1.532342 - 0.009598\,IBA$ | 0.4298 | 0.062 |
| | $c_1$ | $-9.691597 - 0.061143\,IBA$ $+3.053497\,ln(IBA)$ $-36.567205/IBA - 1.060006/IAGE$ | 0.5259 | 0.009 |
| | $c_2$ | $-18.942824 + 0.855515\,IBA$ $-2.476984\,IBABR + 45.69871\,BR$ | 0.3719 | 0.412 |
| | $k$ | 4 | | |

**Equations to estimate control (untreated) yield**

The control net basal area yield equations are of the general form

Net basal area yield: $y = e^{(b_0+b_1 X)} X^{b_2} - k$

Annual yield: $\frac{dy}{dX} = e^{b_0}(e^{b_1 X} b_2 X^{b_2-1} + X^{b_2} b_1 e^{b_1 X})$

Details of the fitting procedure are given in Appendix 1. The following two tables (A2.3 and A2.4) give the values or equations for estimating the $b_i$ coefficients.

TABLE A2.3. Coefficients for estimating crop tree control yield

| Treat. | Coefficient ($b_i$) | Value or equation of coefficient | Adj. $R^2$ | $\sqrt{MSE}$ |
|---|---|---|---|---|
| T0F0 | $b_0$ | $-0.046298 + 1.006281\ ln(IBAC)$ | 0.9999 | 0.007 |
| | $b_1$ | $e^{-5.412167-5.0396848\,(1/IBAC)}$ | | |
| | | $.e^{36.551558\,(1/IAGE)+32.076445\,(1/SITE)}$ | 0.6596 | 0.165 |
| | $b_2$ | $e^{-1.943134+10.639607\,(1/IBAC)}$ | | |
| | | $.e^{-50.616669\,(1/SITE)} - 0.03$ | 0.7651 | 0.266 |
| T1F0 | $b_0$ | $0.64174 + 0.231314\ IBAC$ | | |
| | | $-0.008128\ IBAC^2 + 0.000118\ IBAC^3$ | 0.9996 | 0.011 |
| | $b_1$ | $[54.785613 - 1158.859583/IAGE$ | | |
| | | $+120.077184/IBAC]^{-1}$ | 0.4403 | 5.243 |
| | $b_2$ | $e^{2.33532-1.532141\,ln(IAGE)} - 0.02$ | 0.6655 | 0.322 |
| T2F0 | $b_0$ | $0.548659 + 0.250287\ IBAC$ | | |
| | | $-0.009255\ IBAC^2 + 0.000139\ IBAC^3$ | 0.9998 | 0.008 |
| | $b_1$ | $e^{-2.834509+(18.610058/IAGE)-3.126107\,BR}$ | 0.7693 | 0.101 |
| | $b_2$ | $e^{(-0.141569-1.640098\,ln(IAGE)+8.110852\,BR)} - 0.02$ | 0.8186 | 0.256 |

TABLE A2.4. Coefficients for estimating stand control yield

| Treat. | Coefficient ($b_i$) | Value or equation of coefficient | Adj. $R^2$ | $\sqrt{MSE}$ |
|---|---|---|---|---|
| T0F0 | $b_0$ | $2.295244 + 0.043369\ IBA$ | | |
| | | $-0.000220\ IBA^2$ | 0.9977 | 0.014 |
| | $b_1$ | $e^{-4.740529+27.683182\,(1/IBA)}$ | 0.3846 | 0.240 |
| | $b_2$ | $e^{-1.429752-0.059205\ IAGE}$ | 0.6383 | 0.615 |
| T1F0 | $b_0$ | $1.809327 + 0.068510\ IBA$ | | |
| | | $-0.000544\ IBA^2$ | 0.9994 | 0.007 |
| | $b_1$ | $0.052450 - 0.000874\ IBA$ | 0.4831 | 0.007 |
| | $b_2$ | $e^{-5.968412+77.869978\,(1/IAGE)}$ | 0.3993 | 0.749 |
| T2F0 | $b_0$ | $1.634243 + 0.081555\ IBA$ | | |
| | | $-0.000780\ IBA^2$ | 0.9983 | 0.011 |
| | $b_1$ | $0.112193 - 0.200386\ BR$ | | |
| | | $-0.000011445\ SITEAGE$ | 0.5990 | 0.005 |
| | $b_2$ | $e^{-2.058243-0.001474\ AGEBA} - 0.01$ | 0.8024 | 0.437 |